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ACCELERATED STRESS TESTING OF SOLAR PHOTOVOLTAIC MODULES

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16. Abstract

In 1974, the U.S. Coast Guard began investigating solar photovoltaic arrays as power sources for marine aids to navigation. Initially, 53 systems consisting of a solar array, battery, and a flashing lamp load were placed in a rooftop test facility adjacent to Long Island Sound in Groton, CT. Within two years, the solar arrays of 25 systems had no power output thereby indicating failure. Effects of the marine environment were judged to be responsible for the failures. In order to use solar arrays on operational aids to navigation, much greater reliability was essential. Consequently, development work was initiated on an accelerated stress test system that would rapidly identify solar photovoltaic modules capable of surviving in the marine environment.

This interim report traces the history of accelerated stress testing of solar photovoltaic modules carried out at the U.S. Coast Guard R&D Center. It describes the military standard tests to which the prototype modules were exposed to and the results of that exposure. The report traces the evolution of the simultaneous multiple stress test to the present marine environment screening test. The results of exposure to the marine environment screening test of 136 test modules are reported.

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METRIC CONVERSION FACTORS

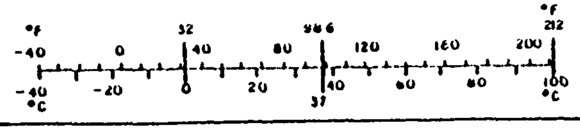
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1.0 INTRODUCTION

In 1974, the U.S. Coast Guard began investigating solar photovoltaic arrays as power sources for marine aids to navigation. Initially, 53 systems consisting of a solar array, battery, and a flashing lamp load were placed in a rooftop test facility adjacent to Long Island Sound in Groton, CT. Within two years, the solar arrays of 25 systems had no power output thereby indicating failure. Effects of the marine environment were judged to be responsible for the failures. In order to use solar arrays on operational aids to navigation, much greater reliability was essential. Consequently, development work was initiated on an accelerated stress test system that would rapidly identify solar photovoltaic modules capable of surviving in the marine environment.

This interim report traces the history of accelerated stress testing of solar photovoltaic modules carried out at the U.S. Coast Guard R&D Center. It describes the military standard tests to which the prototype modules were exposed to and the results of that exposure. The report traces the evolution of the simultaneous multiple stress test to the present marine environment screening test. The results of exposure to the marine environment screening test of 136 test modules is reported. A second interim report is planned which will perform a comparison of the behavior of modules which are aging in the marine environment to the behavior of the modules which have completed the marine environment screening test. A third report is planned to address the issue of acceptance testing of modules for Coast Guard use. The various testing techniques utilized for photovoltaic modules in the United States and Europe will be reviewed and a testing sequence will be recommended.

2.0 DISCRETE ENVIRONMENTAL STRESS TESTING

2.1 Description of Modules

In 1975, modules from four solar manufacturers were procured for environmental testing. These modules represented a variety of construction techniques and materials. Table 1 lists the encapsulation materials used in the initial test modules.

TABLE 1

MODULE MATERIALS

PANEL MANUFACTURER	COVER	SUBSTRATE	POTTANT
Solar Power	Lexan	Sylgard	Sylgard
Solarex	RTV	Fiberglass	RTV
OCLI	Glass	Aluminum frame	RTV 615
Spectrolab	R-4	Aluminum I-beam	R-4

Figure 2-1 shows the various modules tested.

2.2 Discrete Stress Tests

A test plan was developed for accelerated stress testing of the modules in an attempt to identify modules that were capable of surviving in the marine environment. The tests were conducted at the facilities of the Naval Underwater Systems Center, New London, CT.

Six discrete stress tests were selected based on similar military standard tests. (See table 2.) After each stress test, an illuminated I-V curve of each module was taken to ascertain the effect a particular test had on the electrical characteristics of the module.

2.2.1 Temperature Shock

The temperature shock facility consists of two 24" by 24" chambers which can each be set at a different temperature. The test specimen is placed in one chamber for the required time and then transferred rapidly to the other by means of an elevator.

The individual tests were run with each of the chambers set at four different temperatures. The test temperatures were:

SET NUMBER	LOW TEMPERATURE	HIGH TEMPERATURE
1	-20°C (-4°F)	15°C (60°F)
2	-30°C	50°C
3	-40°C	90°C
4	-60°C (-76°F)	120°C (248°F)

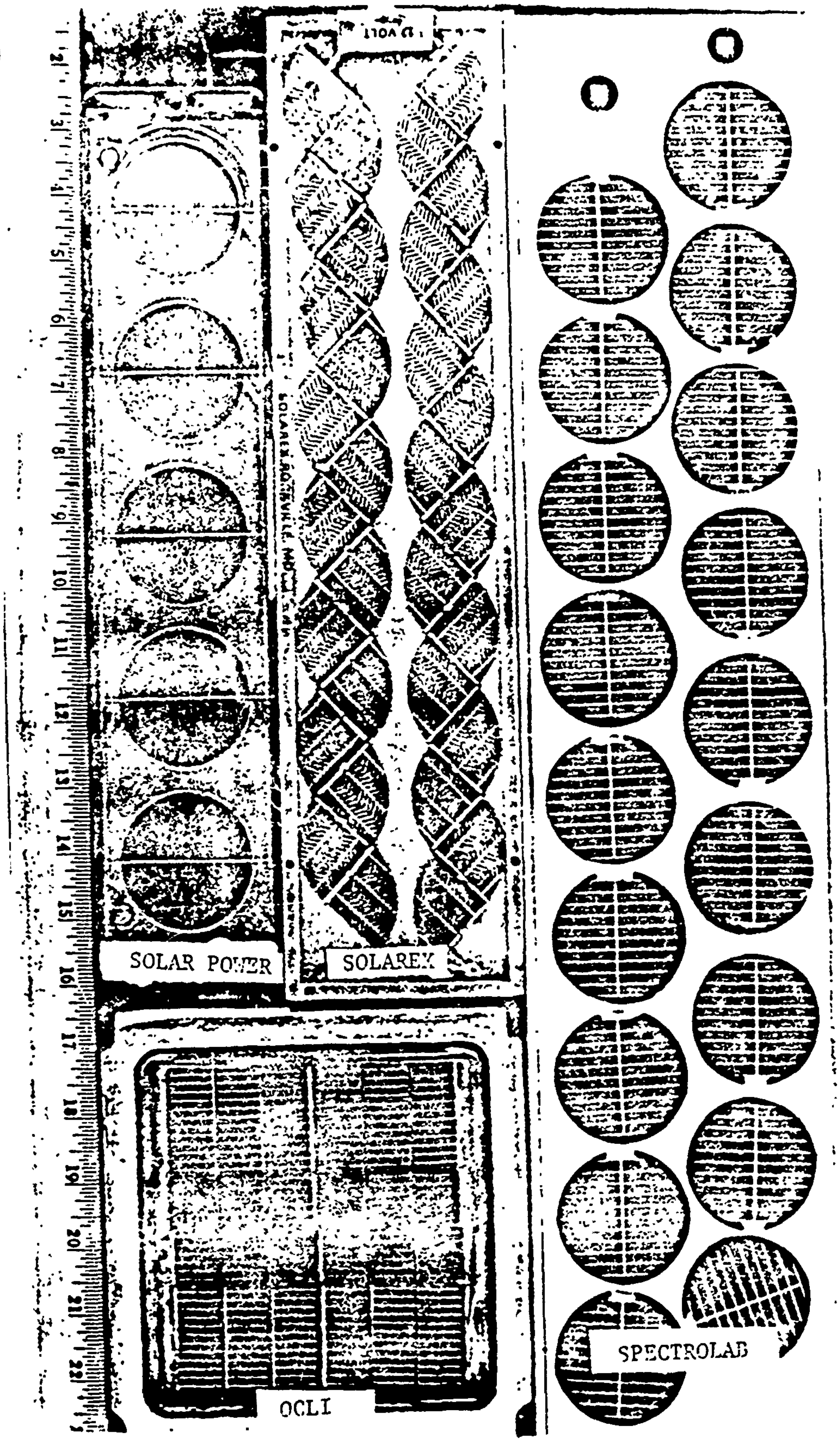

FIGURE 2-1

Modules Subjected to Discrete Environmental Testing

TABLE 2

ENVIRONMENTAL STRESS TESTS

TEST TITLE	TEMPERATURE SHOCK	IMMERSION	MECHANICAL SHOCK	VIBRATION	HUMIDITY	SALT FOG
TEST SIMILAR TO	MIL-STD-810 METHOD 503	MIL-STD-202 METHOD 104A CONDITION B	MIL-STD-202 METHOD 213B	MIL-STD-810 METHOD 514 PROCEDURE I	MIL-STD-810 METHOD 507 PROCEDURE I PARTS 1 AND 2	MIL-STD-810 METHOD 509
TEST SET #1	-20°C to +15°C 3 CYCLES	-2°C to 65°C 2 CYCLES	25g's 9 SHOCKS	[1]	71°C to 28°C 3 CYCLES	35°C 24 hours
#2	-30°C to +50°C 3 CYCLES	-2°C to 65°C 2 CYCLES	50g's 9 SHOCKS		71°C to 28°C 3 CYCLES	35°C 24 hours
#3	-40°C to +90°C 3 CYCLES	-2°C to 65°C 2 CYCLES	100g's 9 SHOCKS		71°C to 28°C 3 CYCLES	35°C 24 hours
#4	-60°C to +120°C 3 CYCLES		200g's 9 SHOCKS			35°C 24 hours
#5						35°C 24 hours

[1]0-1000 Hz resonance search limited to 1g. resonance determined by maximum amplitude in X, Y, and Z directions.

The test began with temperature setting #1. Each test group of modules was inserted into the low temperature chamber for 30 minutes, where the modules were allowed to cool. The modules were then transferred to the high temperature chamber for 30 minutes. This cold-hot cycle was repeated six times. At the end of this period, the modules were removed from the chamber. After at least 10 minutes at room temperature ($28^{o} \pm 10^{o}C$), I-V curves were taken. This procedure was repeated three more times for each of the remaining temperature setting. A total number of 24 cycles (i.e., 6 cycles times 4 sets) were completed.

This test procedure is similar to MIL-STD-810B Method 503, except for the use of four progressive temperature setting and the length of time per cycle. The cycle time was shortened from 8 hours to 1 hour because of the small mass of the modules.

2.2.2 Immersion

The immersion tests consisted of placing the modules in a low temperature bath for a specified period, transfer to a high temperature bath, and repeat. The temperature difference stresses the module and increases the chance of liquid penetration.

The liquid used was a salt water solution simulating sea water. The bath temperatures employed were $-2^{o}C$ ($29^{o}F$) and $65^{o}C$ ($150^{o}F$). Three modules of each type, or a total of 12, were exposed at one time. The soak times were as follows:

a. Low temperature soak for 15 minutes
b. High temperature soak for 15 minutes

After six cycles, the modules were thoroughly washed and dried. I-V curves were taken to monitor module performance.

This test was similar to MIL-STD-202 Method 104A Test Condition B with a reduction in the low temperature.

2.2.3 Shock (Specified Pulse)

The shock test involved rigidly mounting the sample modules to a steel plate using the method normally specified by the solar module manufacturer. The plate was dropped from a fixed height to subject the modules to a specified peak g force, wave form, and time duration. The fixture was rotated such that the shock is administered in the x, y, and z directions. Three shocks in each direction (+x, -x, +y, -y, +z, and -z) were performed. After each set of shocks, an I-V curve was taken to monitor the module performance.

For each orthogonal direction, the maximum g force was sequentially increased. Four levels were administered: 25, 50, 100, and 200 g's. Thus each module was subjected to 72 shocks (3 shocks times 6 directions times 4 levels). A half sine shock pulse of two-millisecond duration was utilized.

This test was similar to MIL-STD-202 ' :thod 213B except that 72 instead of 18 shocks per module were employed due ' o the graduated shock levels.

2.2.4 Vibration

Programmable vioration tables in various sizes were utilized for these tests. The method of MIL-STD-810, Method 514, Procedure I, Parts 1 and 2 only, was used with the following modification. The vibration frequency was varied from 0 to 1000 Hz with the table held at a constant acceleration of 0.5 to 1.0 g until the most severe resonant frequency was found for each orthogonal direction (x, y, z).

The modules were then excited at the resonant frequency for each orthogonal direction and the highest tolerable amplitude was noted.

2.2.5 Humidity

This test employed a large chamber which has the capability of producing very high temperatures with 95 to 97 percent relative humidity.

Twelve modules were run at one time with the chamber maintained at greater than 95 percent relative humdity. One cycle consisted of a one-hour exposure at 71°C (160°F) and then a one-hour exposure at 28°C (82°F). A complete cycle required two hours of chamber time at steady-state conditions, but a long period was required to reach these levels. Consequently, only three cycles per day were completed. The test exposed the modules to a total of nine cycles.

The test is similar to MIL-STD-8910 Method 507, Procedure I, with shortened time.

2.2.6 Salt Fog

The modules were exposed to an atomized salt fog solution of sodium chloride containing $5 \pm 1\%$ of salt by weight and at a temperature of 35 ± 8°C in a chamber held at $\overline{3}5$°C (95°F) for a period of 24 hours. After each 24-hour period, the salt deposits were washed from the sensitive surface of the modules in running water not warmer than 38°C (100°F) and inspected for corrosion. An I-V curve of each module was taken. The modules were replaced in the chamber and the test continued. Maximum exposure time was four days (96 hours).

The test is similar to MIL-STD-810, Method 509.

2.2.7 Electrical Test Equipment

In order to monitor the electrical performance of the test modules, a "solar simulator" was constructed. The simulator consisted of fifteen 600-watt quartz-iodine lamps with parabolic reflectors. The lamps provided a uniformly illuminated area into which the solar modules were placed. A Hewlett-Packard 9830 computer provided the control function for a variable loading device which was placed across the terminals of the module. The current through and the voltage across the load was recorded as the load varied. From the values, an illuminated current versus voltage I-V curve was made. Electrical degradation was monitored by observing changes in the I-V curve.

2.3 Results and Conclusions

Three modules of each of the four types were subjected to each discrete environmental test. It was found that the samples of the four types of solar arrays survived all of the environmental tests. Malfunctions could only be induced by subjecting the modules to unrealistic environmental conditions, for example, 400 g shocks. One purpose of this first series of tests was to determine maximum tolerable levels, that is, the degree of severity that would induce failures. It was discovered that these sample modules were sturdier than suspected, and further testing of the types performed would not yield meaningful data.

The results of the salt fog test were as follows: after the first 23-hour cycle, the three OCLI modules showed corrosion on the cast aluminum housings. No corrosion was seen on the Spectrolab modules. The Solarex units had evidence of delamination which continued to worsen during each cycle. Slight corrosion on the rear terminals of the Solar Power modules was also observed. However, no electrical performance losses were detected resulting from these salt fog tests.

Shocks of from 25 to 400 g's were administered in the ±X, ±Y, and ±Z directions during the mechanical shock test. All of the modules were able to survive the 200 g level shocks which was the maximum intended level. At 400 g's fractures were produced in the glass-mounted arrays. This level was judged unrealistic and would probably never occur under operational conditions. Thus, all module types passed the shock test.

In the vibration tests, the resonant frequencies were determined for each module in the orthogonal directions (x, y, z). A series of tests were performed at increasing amplitudes. Realistic amplitudes produced no significant performance degrading effects on the test modules. Only minor structural failures were induced in the samples.

The humidity, temperature shock, and immersion test also did not produce any observable electrical degradation in the modules.

The discrete environmental stress tests were able to induce what appeared to be symptoms of failure in modules but no actual electrical failures occurred. At this stage of development, it was concluded that the analysis of symptoms of failure required too much subjective interpretation. Consequently, discrete environmental stress testing was terminated in favor of testing that would produce measurable electrical degradation of modules similar to what was observed on the rooftop.

3.0 MULTI-STRESS TESTING DEVELOPMENT

In considering the marine environmental effects on solar photovoltaic modules, it was conjectured that the combination of environmental stresses acting simultaneously were responsible for the electrical degradation observed. A multi-stress testing chamber was constructed to provide simultaneous multiple stress on the modules.

3.1 Pressure, Immersion, Temperature (PIT) Test Chamber

In selecting a multiple-stress testing system, the following guidelines were adopted:

1. All environmental mechanisms that act on the solar array should be acting simultaneously in the accelerated tests.

2. The severity of stressing should be sufficient to induce failures that could be measured quantitatively.

3. The test facility should be machine controlled so the solar modules can be cycled to failure without incurring exorbitant costs.

In reviewing the failures observed on the rooftop and on solar panels deployed on buoys, it was concluded that the combination of the salt water and temperature changes were responsible for the electrical failures. A chamber was constructed that would subject the modules to these types of stresses. The modules while inside the chamber were subjected alternatively to immersion in 45°C salt water and 3°C salt water. Concurrently, the chamber was periodically pressurized to 5 psig. The air pressurization was included to attempt to accelerate the failure mechanisms and reduce the test time. Figure 3-1 illustrates the cycling a module endures.

3.2 Initial (PIT) Test Results

One module from each of the four manufacturers (whose modules underwent the discrete environmental stress tests) was selected to be tested in the initial PIT cycling segment. The cycling was interrupted periodically and the following tests conducted:

a. The module was washed in warm water to remove the mineral deposits.

b. The I-V performance curve of the module was measured using the artificial light source.

c. The module was examined for obvious defects or incipient failures.

The results of these periodic measurements are shown in table 3.

The maximum power is defined as the point on the I-V curve where the product of the current and voltage is a maximum. The fill factor is defined as the ratio of the maximum power to the product of the short circuit current and the open circuit voltage.

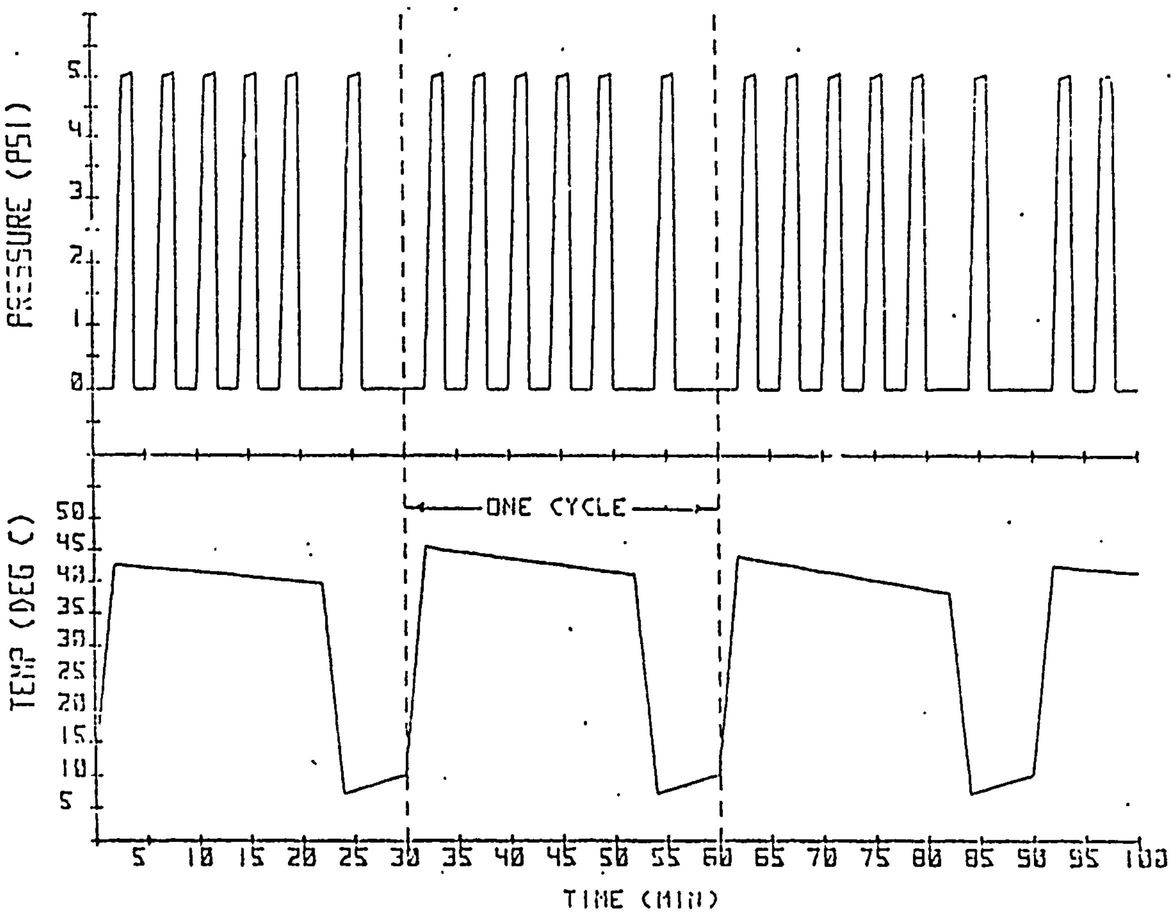

FIGURE 3-1

Pressure and Temperature Cycling Sequence

TABLE 3

Changes in Electrical Performance of Modules Due to PIT Cycling

Spectrolab CYCLE	MAXIMUM POWER (watts)	EFFICIENCY (percent)	FILL FACTOR
0	3.070	10.88	0.57
494	3.010	9.85	0.54
1,078	0.947	2.45	0.29
1,782	0.138	0.35	0.27
2,218	0.080	0.00	0.01

Solar Power CYCLE	MAXIMUM POWER (watts)	EFFICIENCY (percent)	FILL FACTOR
0	1.841	9.14	0.69
494	0.929	7.97	0.78
1,078	0.879	7.71	0.67
1,782	0.872	7.65	0.78
2,218	0.816	7.16	0.65

Solarex CYCLE	MAXIMUM POWER (watts)	EFFICIENCY (percent)	FILL FACTOR
0	0.995	5.44	0.42
494	0.919	5.02	0.48
1,078	0.828	4.40	0.37
1,782	0.839	4.56	0.30
2,218	0.843	4.64	0.37

OCLI CYCLE	MAXIMUM POWER (watts)	EFFICIENCY (percent)	FILL FACTOR
0	1.583	12.88	0.65
494	1.577	12.84	0.68
1,078	1.565	11.95	0.68
1,782	1.559	11.90	0.69
2,218	1.548	11.75	0.68

All four modules demonstrated some type of electrical degradation. The Solar Power Corporation module and the Spectrolab modules underwent steady electrical degradation. The Spectrolab modules failed completely after 2,218 cycles. The solar power module experienced a loss of over 50 percent in maximum power over the cycling sequence. The OCLI modules had a noticeable loss in open circuit voltage toward the end of the cycling. Due to the inaccuracy in the solar simulation equipment, this change is not readily apparent in the output data but was quite noticeable in the I-V curve. The Solarex Corporation modules had a very poor initial efficiency and fill factor. Changes are evident in its output over time. The inaccuracy of the solar simulation equipment is responsible for the ambiguity in measurements.

With all four modules exhibiting some electrical degradation, the initial PIT cycling had been successful in inducing changes in the modules that were quantifiable.

Comparisons were then made between the failures and degradation mechanism of the rooftop and buoy-deployed modules to the failures and mechanisms observed in the modules that had undergone PIT cycling. The results are compiled in table 4. There was enough similarity in failures to warrant further development of the PIT test facility.

3.3 Freeze Test Results

To further refine the PIT test sequence, an effort was initiated to evaluate the effects of a freezing cycle in the PIT test sequence. Eight panels of three different manufacturers were chosen: Solar Power Model 1002, OCLI Model CSP-14, and Spectrolab Model LECA I-BEAM. Four of each type panel were designated control units and were subjected to a PIT testing sequence without frost cycle. The other four panels of each type were subjected to this same PIT testing sequence with the inclusion of a periodic frost cycle.

Prior to the testing sequence, electrical measurements on all panels were made. The panel was resistively loaded to a test voltage of 0.375V per cell times the number of cells in series per panel. The current output at the test voltage was measured and this is the designated "as new" current reading against which all subsequent readings were compared.

The testing sequence went as follows:

a. All panels were subjected to 350 cycles of the PIT. The control panels were removed while the remainder were subjected to eight hours of sub-freezing temperatures. The panels were then measured.

b. This process was repeated at 609 cycles, 865 cycles, and 1,139 cycles. Additionally, a measurement of all the panels was made at 433 cycles without a freeze cycle.

Results are summarized in figures 3-6 through 3-8. The data presented is given as "percent of new output" values. These are expressed relative to the initial current output. Each data point is the mean output of the four-panel group. The bars represent the standard error of the mean of data points.

TABLE 4

COMPARISON OF FAILURE MODES

ROOFTOP AND BUOY MODULES	DISCRETE ENVIRONMENT STRESS TEST MODULES	PIT MODULES
OCLI		
Water passed by gasket and oxidized terminal lug until no current passed.	Same except water did not reside long enough to fully oxidize terminal lugs.	Faint condensation occurred after 1702 cycles. Water droplets appeared after 2210 cycles. Water did not reside long enough to fully oxidize terminal lugs.
No strain relief on RTV 615 potting - potting tears away.	Same	Same
Scotch tape holding cells in place for potting wicks in water.	Same	Same
SPECTROLAB		
Poor intercell connections (most cases).	Some cases	Some cases
Construction different from modules in other two tests.	Extensive delamination between fiberglass cloth, R4, and aluminum substrate caused by temperature shock, humidity, immersion, impulse shock, and vibration.	Same delamination. R4 was punctured by flexing of intercell connects, water entering oxidized cells and grids caused failure.
Intercell connections on new modules protrude through conformal coating.	Same	Same
SOLAR POWER CORPORATION		
External corrosion of terminal screws.	Same	Same. Also extensive internal corrosion where screw meets busbar.
Loss of fill factor in I-V curves after considerable environmental exposure.	Not observed.	No loss in fill factor observed. However, significant loss in I_{SC}.
Not observable due to method of arraying the modules.	Sygard on rear of modules delaminates and peels away easily (after each test).	Same
Not observed.	Not observed.	Cracks along edge of lexan cover.
SOLAREX		
Extensive delamination of conformal coat from cells and substrate.	Same	Same
Conformal coat tears and punctures under rough handling.	Same	Same
Not observed.	Not observed.	Extensive corrosion on back of all cells starting after 494 cycles.
Teflon wire wicks water into busbar where water oxidizes busbar.	Same	Same

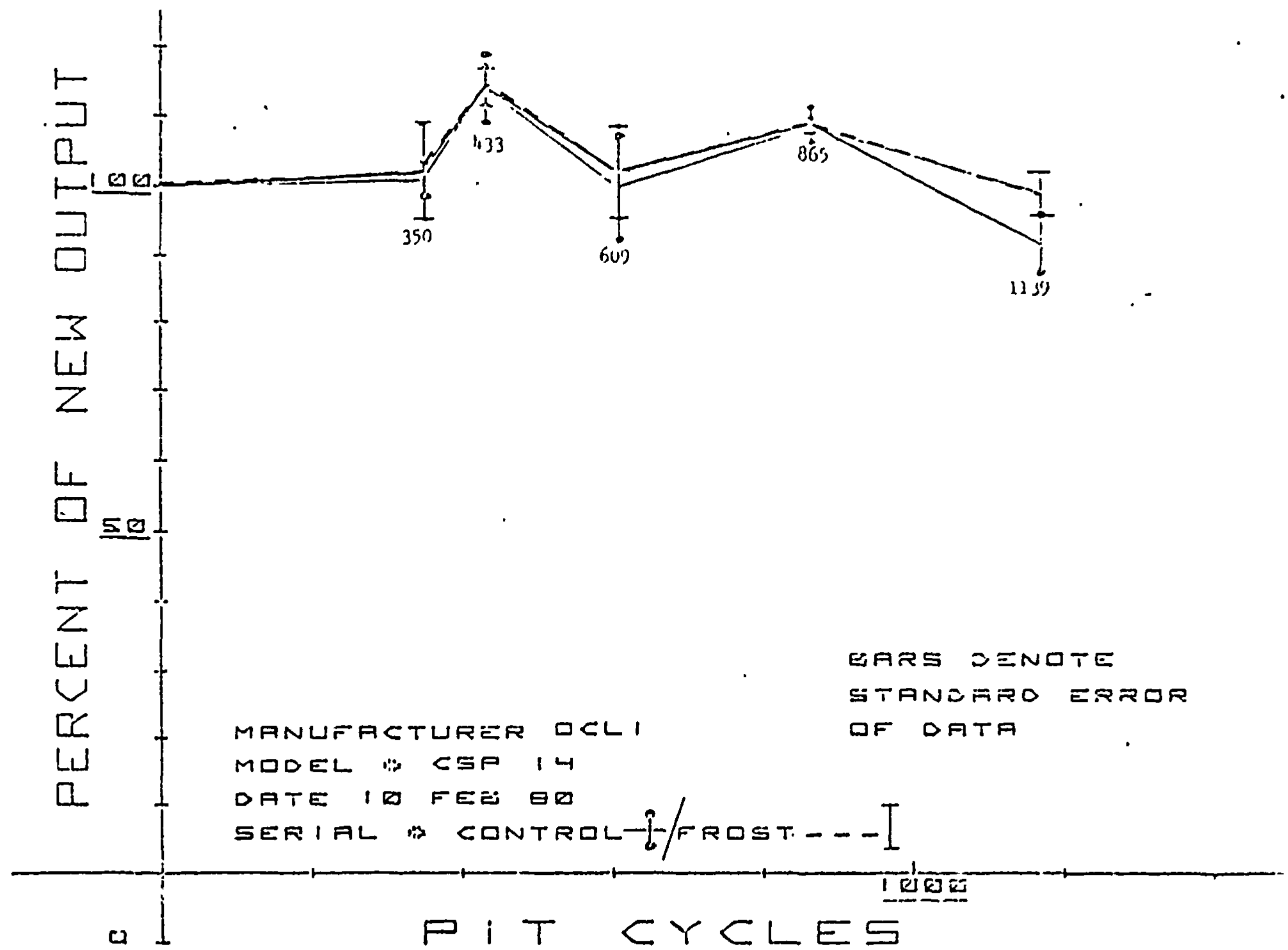

FIGURE 3-2

Freeze Test Effects on OCLI Module

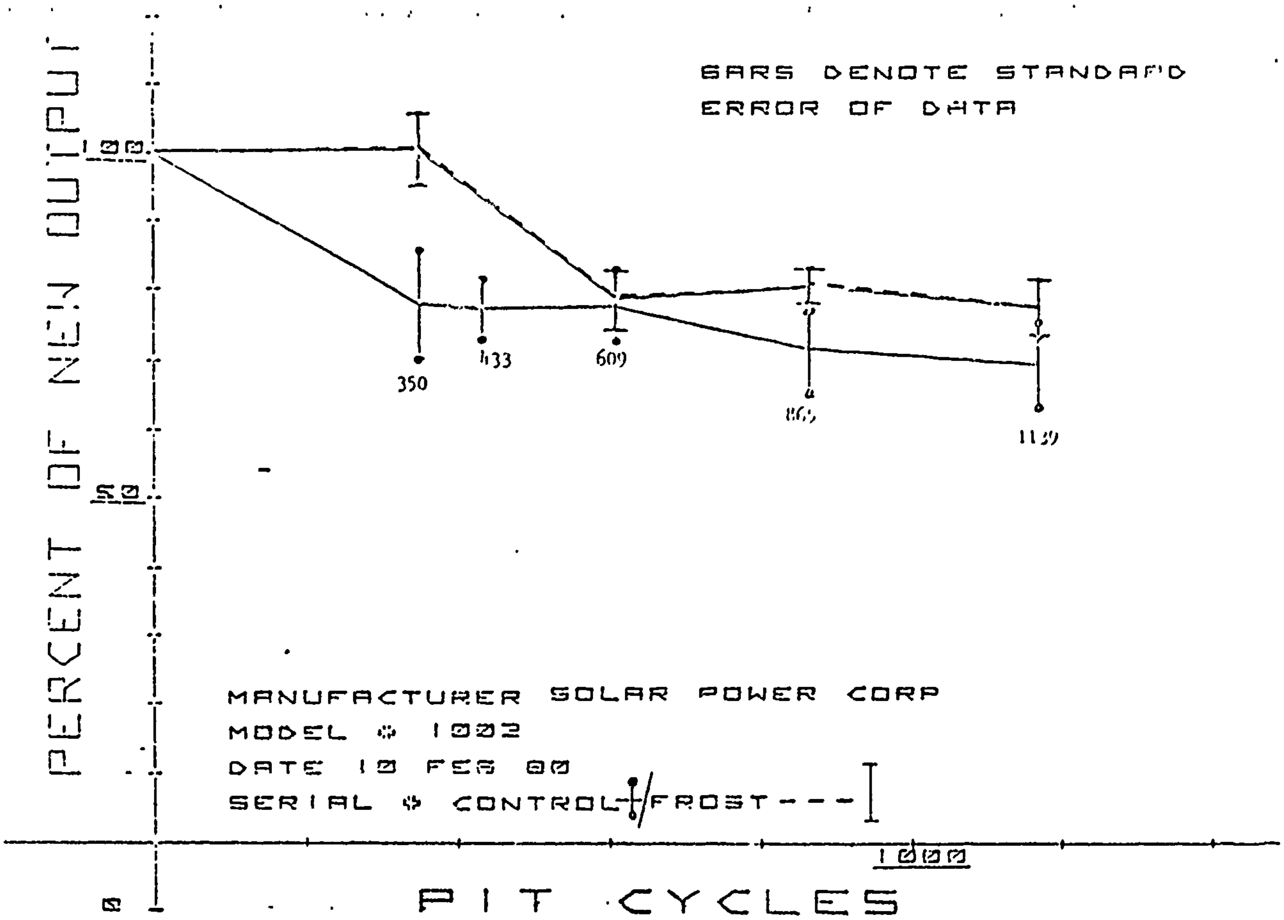

FIGURE 3-3

Freeze Test Effects on Solar Power Module

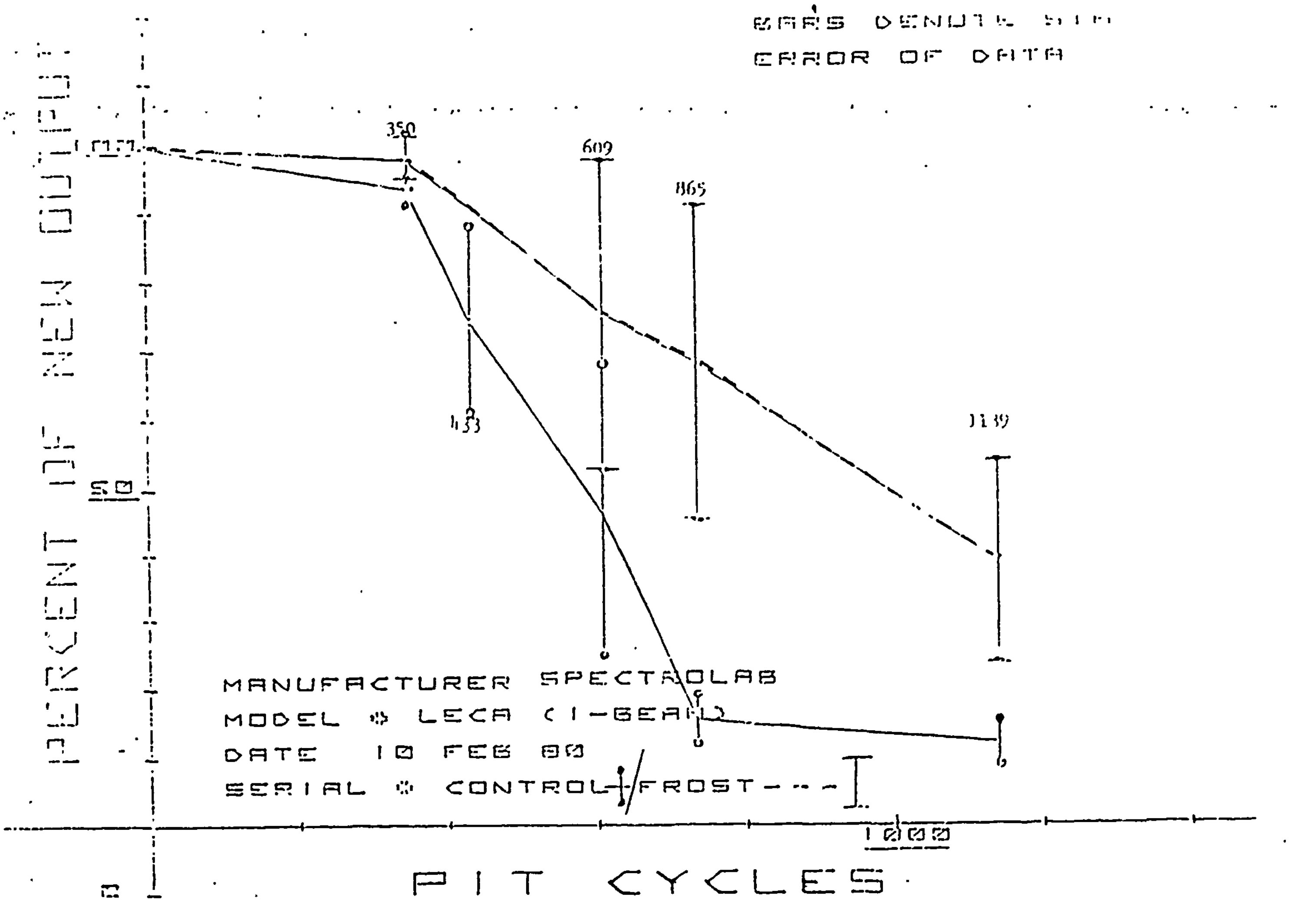

FIGURE 3-4

Freeze Test Effects on Spectrolab Module

The portions of the curves above 100 percent reflect the variability in temperature and insolation among the panels at the different times (number of cycles) data was taken. However, these parameters were stable at each point in time.

The data was analyzed by testing certain hypotheses. The first hypothesis: there is no significant difference in the data of the control group of each type compared to data from the frost cycle group. This hypothesis was not rejected (even as low as 65 percent confidence level) for either the OCLI Model CSP-14 or the Solar Power Model 1002. For the Spectrolab LECA I-BEAM, after 865 cycles, the hypothesis was rejected at the 95 percent confidence level. However, the panels that were subjected to the frost cycle performed better than the panels that did not go through this cycling.

Based on the test results, it was concluded that the frost cycle did not accelerate the degradation of panels subjected to the PIT test. In the case of the Spectrolab panels, the degradation time was extended as a result of the freeze cycle. Further testing of a freeze cycle was terminated and the addition of a freeze cycle to the PIT testing sequence was dropped from consideration.

3.4 Conclusions

The PIT testing sequence had been successful in inducing measurable electrical degradation in solar photovoltaic modules. The freeze test would not be included in the PIT test as it did not accelerate failures in the modules tested.

The output measurements obtained by the solar simulator had large variations which limited the interpretation of the results of the stress testing. In the full-scale development of the PIT test, the accuracy and repeatability of measurement techniques should be improved.

4.0 MARINE ENVIRONMENT SCREENING TEST DEVELOPMENT

Based on the initial success of the PIT test sequence, a full-scale testing program was initiated. Seventeen different models of various construction materials and designs were procured from commercial solar manufacturers. Table 4.1 lists the materials and construction techniques of the various modules.[1]

4.1 Marine Environment Screening Test Sequence

The test procedure consists of the following steps:

a. Measure Illuminated I-V Curve I: The current versus voltage curve was obtained at the commercial solar simulator owned by Solar Power Corporation in Boston, MA. Each panel, prior to testing of any kind, was placed on the solar simulator to obtain a baseline I-V curve against which the effects of any subsequent tests can be noted. This solar simulator exhibits a repeatability of around two percent. It was utilized to correct the measurement problem noted in the early testing.

b. Pre-Exposure Test: Each panel was subjected to alternate spraying with fresh water and drying (using eight GE 275-watt sunlamps and four GE 40BL ultraviolet lamps). This pre-exposure test continued for 49 days. The pre-exposure test was included to provide UV weathering and wet-dry cycling. One panel failed due to the pre-exposure.

c. Measure Illuminated I-V Curve II: When compared to Curve I, this curve reflects the effects of the pre-exposure on the panel and represents the state-of-the-panel prior to placing it in the PIT test chamber. This curve was obtained at Solar Power Corporation.

d. PIT Test: Each panel was placed inside the PIT test chamber and subjected to the following sequence of stresses which defines one 28-minute cycle:

1. Immersed in 50°C salt water
2. Pressurized to 5 psig five times
3. Immersed in 5°C salt water
4. Pressurized to 5 psig once

Begin cycle again with immersion in 50°C salt water. Each panel was subjected to 2000 cycles of the sequence of stresses.

e. Measure Illuminated I-V Curve III: This curve represents the state-of-the-panel after PIT cycling, which can be compared to the curve representing the state prior to the PIT cycling and to the original state curve. This curve was obtained at Solar Power Corporation.

f. Failure Analysis: Panels that fail during any part of the testing sequence were disassembled, the cause of the failure was identified (if possible), and a failure report was prepared.

TABLE 5

ARRAY MATERIALS AND CONSTRUCTION TECHNIQUES

PANEL SERIAL NUMBER	ENCAPSULATION TECHNIQUE	COVER	SUBSTRATE	SEALANT/ ADHESIVE/ CELLS	POTTANT	ARRAY INTERCONNECT	TERMINATION	OBSERVATIONS
0500	Rigid lamina envelope	Lexan^{R}	Fiberboard	32 ea, 55mm	2-part RTV	Tin-plated copper	Teflon-coated wire pigtails	
1100	Conformal cover	Silicone rubber	Glass-reinforced polyester	36 ea, 90mm	Silicone rubber	Solder-coated copper	Phenolic junction box	
1200	Rigid lamina envelope	Low iron-tempered glass	Aluminum extrusion	18 ea, 55mm	Silicone GE615	Alloy 110, copper	Barrier strip	
1400	Film laminate	Borosilicate glass	Borosilicate glass	6 ea, 55mm	RTV silicone rubber	Expanded copper mesh	Brass standoffs	
1500	Film laminate	Glass-tempered	Glass	6 ea, 55mm	2-part RTV	Tin-plated copper	Teflon-coated wire pigtails	Brass frame
1600	Rigid lamina envelope	Glass, Sunadex	Tedlar on aluminum	20 ea, 75mm, 1/4 cell	Polyvinyl butyrl	Copper	Amp plug	Anodized Aluminum Frame
1700	Rigid lamina envelope	Glass-tempered	Anodized aluminum	36 ea, 55mm, 1/2 cell	2-part RTV	Solder-coated copper	Junction box	
1800	Conformal cover	Silicone rubber	Glass-reinforced polyester	36 ea, 55mm, 1/2 cell	Silicone rubber	Solder-coated copper	Phenolic junction box	
2000	Conformal Substrate	Glass, soda lime	GE615 RTV inside frame	36 ea, 20mmx20mm square	GE615 RTV	Copper	Posts	Corrosion Resistant Aluminum Frame
2100	Film laminate	Glass	Glass	8 ea, 75mm, 1/4 cell	Dow Corning 184 silicone	0.004 tinned copper	Phenolic box	Anodized Aluminum Frame
2200	Rigid lamina envelope	Glass, Sunadex	Tedlar on aluminum	20 ea, 75mm, 1/4 cell	Polyvinyl butyrl	Copper	Amp plug	
2300	Rigid lamina envelope	Glass, tempered	Stainless steel	36 ea, 75mm, 1/2 cell	Dow Corning 2-part liquid silicone	Copper Lamina Kapton	Posts	Stainless steel frame
2400	Conformal Substrate	Pyrex glass	Tedlar	12 ea, 75mm	Polyvinyl butyrl	Solder-coated copper	Posts	Stainless steel frame
2500	Conformal Coat	Tedlar Vapor Barrier	Aluminum	36 ea, 75mm, 1/4 cell	Polyvinyl butyrl	Solder-coated copper	Posts	
2600	Conformal Substrate	Glass, Sunadex	Tedlar	12 ea, 75mm	Polyvinyl butryl	Solder-coated copper	Posts	Stainless steel frame
2700	Conformal Substrate	Glass, soda lime	GE615 RTV	36 ea, 20mmx20mm square	GE615 RTV	Copper	Wire pigtails	Identical to 2000 without frame
2800	Rigid lamina envelope	Pyrex glass	Aluminum foil vapor barrier	12 ea, 75mm	Polyvinyl butyrl	Solder-coated copper	Posts	Stainless steel frame

4.2 Marine Environment Screening Test Results

Figure 4-1 graphically lists a summary of photovoltaic module performance after 2000 cycles of PIT testing. Table 4-1 is broken down into the following categories:

- Number Tested - The standard sample size was eight modules, nine 0500 series modules, and only six 2300 series modules were tested. We were unable to obtain two additional 2300 series panels. A total of 135 modules were tested.

- Electrical Failures - An electrical failure is defined as 60 percent or less test current output when compared to the test current output prior to PIT cycling.

- Electrical Degradation - Electrical degradation is defined as less than 80 percent but greater than 60 percent test current output when compared to the test current output prior to PIT cycling.

- Visual Degradation - Degradation processes that are visible to the eye but have not caused electrical degradation are classified as visible degradation. Processes included are corrosion on interconnects, cell grids, and water in the interior of the panel. Visual degradation are expected to result in electrical degradation in a short time.

4.3 Failure Analysis

Approximately 46 percent of the modules tested exhibited some type of failure. Four models, Series Numbers 1200, 1400, 2100, and 2300 exhibited no failures. Of the modules that failed, the type of failure and the percentage of the total number tested are illustrated in figure 4-2. By model number, the failures observed were:

0500 - Water in interior of panel due to poor edge sealing. Corrosion at terminal/interconnection interface due to water wicking into the module via Teflon[R]-coated wire.
1100 - Delamination and debonding of pottant.
1500 - Corrosion at terminal/interconnection interface due to water wicking into the module via Teflon[R]-coated wire.
1600 - Water in interior of module.
1700 - Severe corrosion on terminal posts.
1800 - Delamination and debonding of pottant.
2000 - Clouding of pottant due to water penetration.
2200 - Water in interior of module.
2400 - Cell grid corrosion, probable chemical incompatibility.
2500 - Severe delamination and debonding of pottant.
2600 - Cell grid corrosion, probable chemical incompatibility.
2700 - Water in interior of module.
2800 - Delamination and debonding of aluminum foil vapor barrier and pottant. One terminal post fell off.

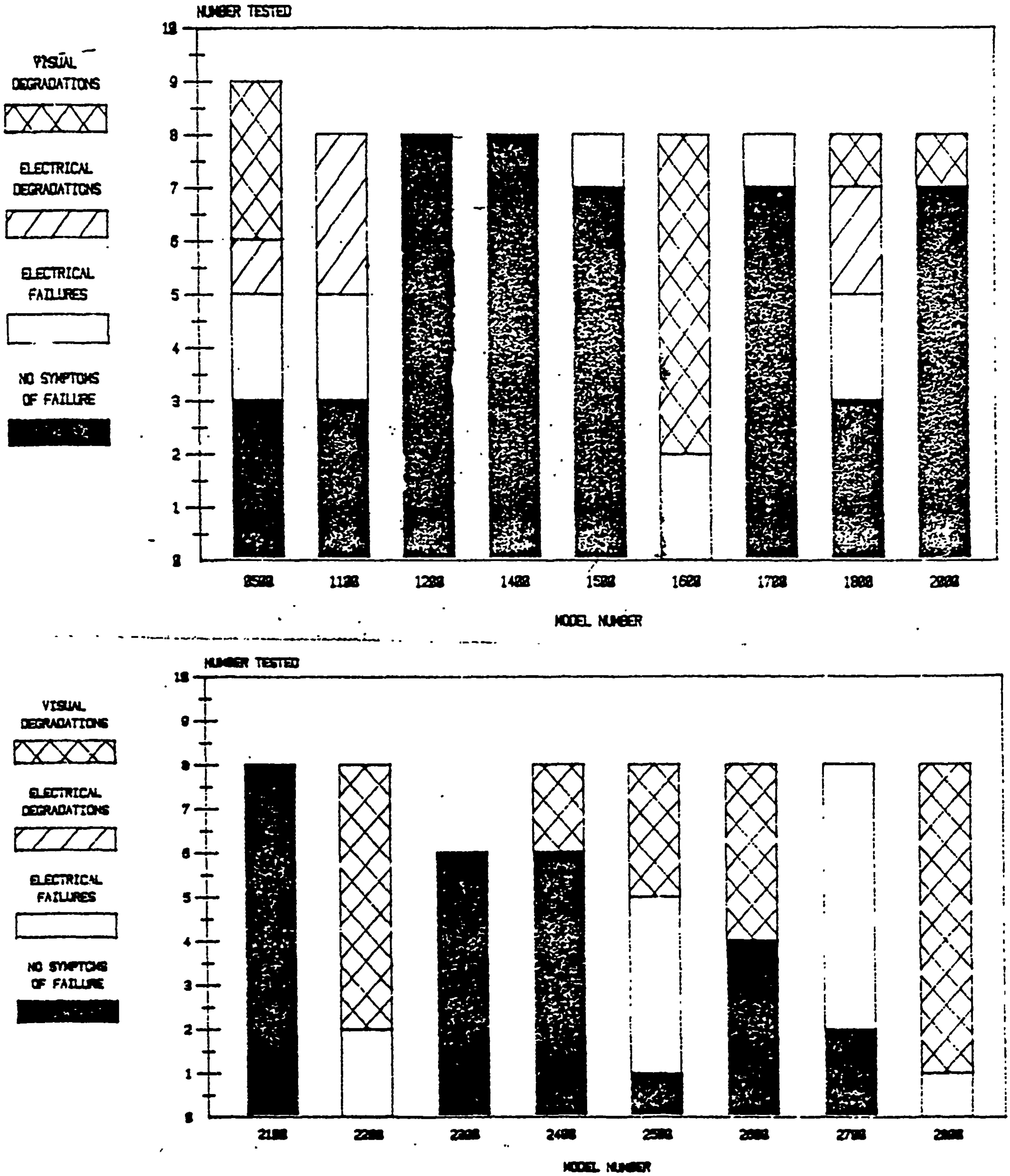

FIGURE 4-1

Module Performance after 2000 Cycles of PIT Testing

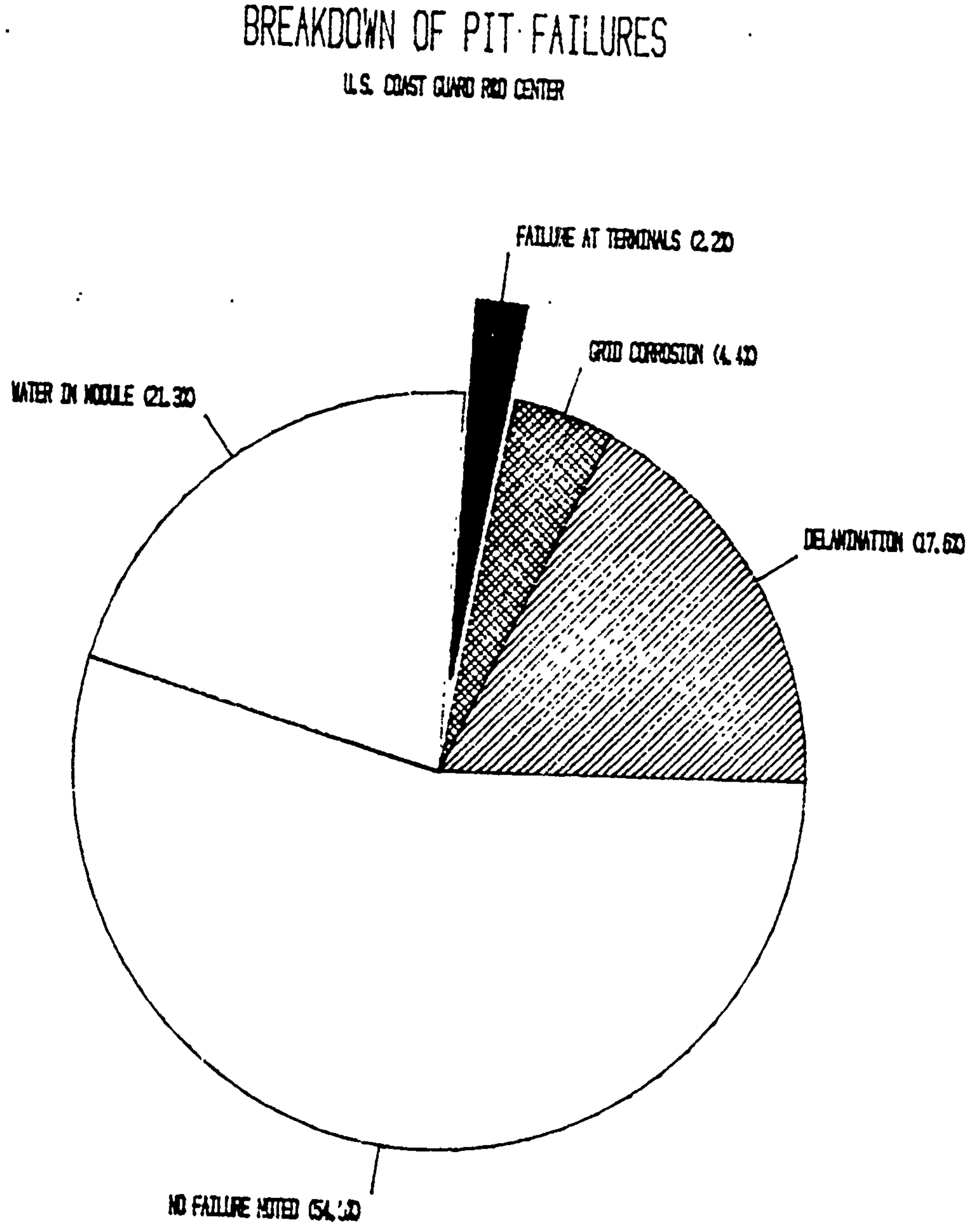

FIGURE 4-2

Breakdown of PIT Failures (Total of Visual Degradation, Electrical Degradation, and Electrical Failures) as a Percentage of the Total Tested

4.4 Conclusions and Recommendations

This report has outlined the Coast Guard's initial program in accelerated stress screening of solar photovoltaics. The discrete environmental tests based on military standard tests were not successful in inducing any electrical failures although visual symptoms of failure were observed. The multiple stress testing based on the Pressure, Immersion, and Temperature (PIT) test chamber was able to induce electrical failures in modules. A marine environment screening test has evolved based on the PIT chamber. This test is time consuming (approximately six weeks duration), costly to perform, and may be unnecessarily harsh on the modules. The marine environment screening test has been successful, however, in inducing electrical failures allowing for a quantitative measure of module performance and probably produces a very high acceleration factor in the failure mechanisms. The actual factor awaits a detailed comparison with a real-time marine environment exposure test which is still in progress.[1]

Since the initiation of testing, progress has been made on visual, qualitative measures of module performance.[2] Analysis of visual failures is not well developed and awaits the build-up of a data base on which to make the qualitative judgements on failure mechanisms. With a better understanding of module failures and failure symptoms, discrete environmental stress tests could be a viable alternative to the multiple stress (PIT) tests. At this point, however, the electrical failures induced by the PIT test allow for the most objective analysis of module performance.

REFERENCES

1. Trenchard, S.E., "Testing of Solar Photovoltaic Arrays for Utilization on Marine Aids to Navigation," CG-D-10-81, November 1980.

2. Acceptance/Rejection Criteria for JPL/LSA Modules, JPL Document 5101-21, Revision B, 3 November 1978.